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## Multi-Objective Optimization in Drilling of GFRP Composites: A Degree of Similarity Approach

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### Abstract

Composite materials have been gaining immense importance in manufacturing industries, particularly in aerospace and automotive industries, due to their excellent properties as compared to other conventional metals. In manufacturing sector, drilling is a very common machining operation; whilst drilling of glass fiber reinforced polymer (GFRP) composite is substantially different from metallic materials due to delamination, fiber pull-out etc. In order to produce satisfactory product quality (GFRP drilled hole), investigations on machining and machinability aspects of GFRP composites are indeed essential. Understanding of the effect of process variables viz. drill speed, feed rate, drill diameter, plate thickness etc. is very important in order to select optimal machining condition towards improving overall machining performance. Therefore, this work focuses on the analysis of drill force (thrust), torque, surface roughness ( $R_a$ ) and delamination behavior (of the drilled hole) as a function of drilling process parameters. The unified aim of this work is to determine an optimal machining environment based on the concept of the 'Degree of Similarity Measure' between each alternative and the ideal solution using alternative gradient and magnitude; TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) and Deng's solution.

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**Keywords:** Glass fiber reinforced polymer (GFRP); Degree of Similarity Measure; TOPSIS; Deng's solution;

### 1. Introduction

In recent years, GFRP composite materials are widely being used in various engineering applications such as automobile, aerospace industries, spaceship and sea vehicle industries because of their unique properties such as high specific stiffness, high specific strength, high specific modulus of elasticity, high damping capacity, good corrosion resistance, good tailoring ability, excellent fatigue resistance, good dimensional stability and a low coefficient of thermal expansion. In aforesaid fields, drilling of GFRP composites is a common machining operation. During drilling of composite materials many problems arise like fiber pull-out, delamination, stress concentration, swelling, burr, splintering and micro cracking etc. which are likely to reduce machining performance. Amongst various defects, delamination (at entrance and exit of the plane of the work piece) is the most critical. Delamination can result in lowering of bearing strength and can be detrimental to the material durability by reducing the in-service life under fatigue loads. Delamination during drilling is due to compressive thrust force

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acting on the uncut portion and peeling force acting on the cut portion. Past investigations showed that the thrust force is the major factor which is responsible for the delamination induced during the drilling GFRP and it mainly depends on the drill materials, drill geometry and feed rate. Many of the research work focused on the behavior of drilling process parameters on machining and machinability aspects of a variety of composite materials. Davim et al. (2004) established a correlation between cutting velocity and feed rate with the specific cutting pressure, thrust force, damage factor and surface roughness, in a GFRP material. A plan of experiments based on the Taguchi's technique was established considering drilling with prefixed cutting parameters in a hand lay-up GFRP material. Kilickap et al. (2010) investigated the influence of the cutting parameters, such as cutting speed and feed rate, and point angle on delamination produced while drilling of GFRP composites. This work focused on the application of Taguchi method and Analysis of Variance (ANOVA) for minimization of delamination influenced by drilling parameters and drill point angle. The conclusion revealed that feed rate and cutting speed were the most influential factor on the delamination, respectively. The best results of the delamination were obtained at lower cutting speeds and feed rates. Langella et al. (2005) presented a mechanistic model for predicting thrust and torque during composite materials drilling. The authors specified the number of coefficients to be experimentally determined and provided a detailed analysis of the problems associated with the action of the chisel edge. They concluded that the model afforded a focused approach to the definition of the most appropriate drill geometry and cutting parameters in composite materials drilling. Latha et al. (2011) studied the influence of drill geometry on thrust force in drilling GFRP composites. Drilling experiments were conducted on composite materials using CNC drilling machine. The influence of drill geometry on thrust force in drilling of composite materials was carried out using three different drill bits, namely, 'Brad and Spur' drill, 'multifaceted' drill, and 'step' drill. Panda et al. (2006) dealt with prediction of flank wear of drill bit using back propagation neural network (BPNN). Drilling operations were performed in mild steel work-piece by high-speed steel (HSS) drill bits over a wide range of cutting conditions. Important process parameters were used as input for BPNN and drill wear was treated as output of the network. Performance of the neural network was found to be satisfactory while validated with experimental results. Singh et al. (2009) conducted experiments by using 8 facet solid carbide drills based on  $L_{27}$  Orthogonal Array (OA). The process parameters investigated were spindle speed, feed rate and drill diameter. Fuzzy rule based model was developed to predict thrust force and torque in drilling of GFRP composites. Tsao et al. (2012) proposed a novel method for the reduction of delamination during composite drilling by active backup force. The applied backup force contributed to suppression of the growth of the delamination at drilling exit by 60-80%. The proposed novel drilling technique revealed the potential for fabrication of composite components at low cost and minor delamination with high feed rate. The objective of the present study is to investigate the effect of the machining variables viz. drill speed, feed rate, drill diameter along with plate thickness (work piece) on the output performances like thrust force, torque, delamination factor and surface roughness (of the drilled hole) during drilling GFRP composites. Based on experimental results, an optimum design of cutting variables (optimal parameter setting) has been obtained by using Deng's similarity measure method in conjugation with Taguchi's optimization philosophy. Results obtained thereof, have been compared with that of TOPSIS.

## 2. The Concept of TOPSIS

The TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method was firstly proposed by (Hwang and Yoon, 1981) for assessing the alternatives before the multiple-attribute decision making. TOPSIS is implemented to measure the extent of closeness to the ideal solution. The basic concept of this method is that the chosen alternative should have the shortest distance from the positive ideal solution and the farthest distance from negative ideal (anti-ideal) solution. Positive ideal solution is composition of the best performance values demonstrated (in the decision matrix) by any alternative for each attribute. The negative-ideal solution is the composite of the worst performance values. The steps involved for calculating the TOPSIS values are as follows:

Step 1: Development of decision Matrix: The row of this matrix is allocated to one alternative and each column to one attribute. The matrix can be expressed as:

$$D = \begin{matrix} & \begin{matrix} A_1 & A_2 & \dots & A_i & \dots & A_m \end{matrix} \\ \begin{matrix} x_{11} & x_{12} & \dots & x_{1j} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2j} & \dots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{i1} & x_{i2} & \dots & x_{ij} & \dots & x_{in} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \dots & x_{mj} & \dots & x_{mn} \end{matrix} \end{matrix} \quad (1)$$

Here,  $A_i$  ( $i=1,2,\dots,m$ ) represents the possible alternatives;  $x_j$  ( $j=1,2,\dots,n$ ) represents the attributes relating to alternative performance,  $j=1,2,\dots,n$  and  $x_{ij}$  is the performance of  $A_i$  with respect to attribute  $X_j$ .

Step 2: Obtain the normalized decision matrix  $r_{ij}$ . This can be represented as:  $r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}}$  (2)

Step 3: obtain the weighted normalized decision matrix,  $Y = [y_{ij}]$  can be found as,  $Y = w_j r_{ij}$  (3)

Step 4: Determine the ideal (best) and negative ideal (worst) solutions:

a) The ideal solution:

$$A^+ = \left\{ \left( \max_i y_{ij} \mid j \in J \right), \left( \min_i y_{ij} \mid j \in J' \mid i = 1, 2, \dots, m \right) \right\} \\ = \{y_1^+, y_2^+, \dots, y_j^+, \dots, y_n^+\} \quad (4)$$

b) The negative ideal solution:

$$A^- = \left\{ \left( \min_i y_{ij} \mid j \in J \right), \left( \max_i y_{ij} \mid j \in J' \mid i = 1, 2, \dots, m \right) \right\} \\ = \{y_1^-, y_2^-, \dots, y_j^-, \dots, y_n^-\} \quad (5)$$

Here,

$J = \{j = 1, 2, \dots, n \mid j\}$ : Associated with the beneficial attributes

$J' = \{j = 1, 2, \dots, n \mid j\}$ : Associated with non beneficial attributes

Step 5: Determine the distance measures. The separation of each alternative from the ideal solution is given by n- dimensional Euclidean distance from the following equations:

$$S_i^+ = \sqrt{\sum_{j=1}^n (y_{ij} - y_j^+)^2} \quad i = 1, 2, \dots, m, \quad S_i^- = \sqrt{\sum_{j=1}^n (y_{ij} - y_j^-)^2} \quad i = 1, 2, \dots, m \quad (6)$$

Step 6: Calculate the Overall performance coefficient closest to the ideal solution:

$$C_i^+ = \frac{S_i^-}{S_i^+ + S_i^-}, \quad i = 1, 2, \dots, m; 0 \leq C_i^+ \leq 1 \quad (7)$$

### 3. Deng's SimilarityBased Method

Deng's similarity-based method (Safari et al., 2013) is a modified form of TOPSIS methodology based on concept that ideal solution is used in such manner so that most preferred alternative should have the highest degree of similarity to the positive ideal increasing or decreasing values. It proposed for evaluating the conflicting index between two alternatives to show the degree conflict between the alternatives.

$$A_i, A^{\mp} = |A_i| |A^{\mp}| \cos \theta^{\mp} \quad (8)$$

$$A_i, A^{\mp} = \sum y_{ij} y_j^{\mp} \quad (9)$$

$$|A_i| = \left( \sum_{j=1}^m y_{ij}^2 \right)^{0.5} \quad (10)$$

$$A^{\mp} = \left( \sum_{j=1}^m y_{ij}^{\mp 2} \right)^{0.5} \quad (11)$$

$$\cos \theta_i^+ = \frac{\sum_{j=1}^m y_{ij} y_j^+}{\left( \sum_{j=1}^m y_{ij}^2 \right)^{0.5} \left( \sum_{j=1}^m y_j^{+2} \right)^{0.5}}, \quad \cos \theta_i^- = \frac{\sum_{j=1}^m y_{ij} y_j^-}{\left( \sum_{j=1}^m y_{ij}^2 \right)^{0.5} \left( \sum_{j=1}^m y_j^{-2} \right)^{0.5}} \quad (12)$$

Step 6: Assessment of the degree of similarity between each alternative and the positive and the negative ideal solution

$$|C_i| = \cos \theta_i^{-+} \times |A_i| \quad (13) \quad S_i^{-+} = \frac{|C_i|}{|A^{-+}|} = \frac{\cos \theta_i^{-+} \times |A_i|}{|A^{-+}|} = \frac{\cos \theta_i^{-+} \times \left( \sum_{j=1}^m y_{ij}^2 \right)^{0.5}}{\left( \sum_{j=1}^m y_{ij}^{-+2} \right)^{0.5}} \quad (13)$$

Step 7: Evaluation of overall performance index:

$$P_i = \frac{S_i^{+}}{S_i^{+} + S_i^{-}}, i = 1, 2, \dots, n \quad (14)$$

## 4. Experimental Part

### 4.1. Experimental Setup and Design of Experiment

Experiments have been executed on CNC drilling machine [MAXMILL 3 axis CNC machine with FANUC Oi Mate MC Contoller, Model No. CNC 2000EG]. Design of Experiment comprises of set of experiments which are to be carried out in a sequential manner for evaluating the response measurements. Taguchi's orthogonal array design of experiment is an economic as well as effective method to examine the effects of the machining parameters through limited number of experiments. The present study focused on the effects of drilling parameters such as drill speed, feed rate and thickness of the composite plates; each varied in four different levels, whereas, drill diameter has been varied in two different levels (as shown in Table 1) on different machining performance features namely thrust force, torque, entry-exist delamination factor and surface roughness of the drilled hole. In this experimentation, mixed level  $L_{16}$  orthogonal array has been used as shown in Table 2.

Table 1: Domain of Experiments

Factors	Unit	Level 1	Level 2	Level 3	Level 4
Spindle Speed	RPM	800	1200	1600	2000
Feed rate	mm/min	100	150	200	250
Plate Thickness	mm	5	6	7	8
Drill diameter	mm	8	10	-	-

Table 2: Design of Experiment

Sl. No.	Spindle Speed (RPM)	Feed Rate (mm/min)	Plate Thickness (mm)	Drill Diameter (mm)
1	800	100	5	8
2	800	150	6	8
3	800	200	7	10
4	800	250	8	10
5	1200	100	6	10
6	1200	150	5	10
7	1200	200	8	8
8	1200	250	7	8
9	1600	100	7	8
10	1600	150	8	8
11	1600	200	5	10
12	1600	250	6	10
13	2000	100	8	10
14	2000	150	7	10
15	2000	200	6	8
16	2000	250	5	8

### 4.2. Workpiece and Tool material

GFRP epoxy composite samples of varying thickness (Fig. 1) have been used for execution of the experimentation. TiAlN coated solid Carbide drill bits [Manufacturer: WIDIA-Hanita, Product: M1308000RT] of different size such as 6 mm and 8 mm have been used for performing drilling operations.

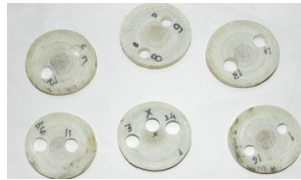


Fig.1: Samples of GFRP epoxy composites after machining

#### 4.3. Machining Performance Characteristics

Drilling operation has been carried out on GFRP composites for assessing performance characteristics such as load, torque, entry delamination factor, exit delamination factor as well as surface roughness of the drilled hole. Thrust force and torque has been evaluated by using Digital Drilling Tool Dynamometer [Make: Medilab Enterprises, Chandigarh, INDIA], whereas, entry delamination factor and exit delamination factor has been assessed by using formula given below:

$$F_d = \frac{D_{\max}}{d} \quad (15)$$

Here,  $F_d$  = delamination factor,  $D_{\max}$  = maximum diameter observed in the damaged zone,  $d$  = diameter of the drill.

Here, surface roughness tester SJ-210 (Make: Mitutoyo) has been used to measure the roughness average value based on carrier modulating principle.

#### 5. Data Analysis

Experimental data presented in Table 3 have been analyzed by following aforesaid procedures. Different techniques have been applied utilizing these output response characteristics. Individual experimental runs (parameters settings) have been dealt as the alternatives and the normalized decision matrix have been calculated. Assuming equal priority weight of the responses (20%), the weighted normalized matrix has thus been computed. According to TOPSIS, the positive ideal and negative-ideal solutions have been determined. The degree of conflict between each alternative and the positive and the negative ideal solution has been determined and Table 4 presents the overall performance coefficient that has been evaluated by using these methodologies: TOPSIS, and Deng's method. Finally, the Taguchi method has been applied on the overall performance coefficient (OPI) to assess the optimal machining parameter by using S/N ratio plot of OPI. Higher the value of closeness coefficient, the corresponding parameter combination is said to be close to the optimal solution. Fig. 2 shows the optimal parametric combination obtained by these different methodologies and it has been noticed that predicted S/N ratios values for these optimal combination individually represent highest value (Refer Table 4) than that obtained for corresponding S/N ratios as depicted in Table 4.

Table 3: Experimental Data

Sl. No.	Torque (N-m)	Thrust (N)	$R_a$ ( $\mu\text{m}$ )	$F_{in}$	$F_{out}$
1	2.943	0.99081	5.098	1.1772395	1.172444785
2	6.867	1.14777	5.036	1.1881515	1.177239452
3	10.4967	1.15758	8.901667	1.2097903	1.175348039
4	17.7561	1.51074	11.30967	1.1709568	1.193944732
5	10.3986	0.81423	5.453	1.1791573	1.198997318
6	13.6359	0.84366	4.816667	1.259549	1.297853424
7	7.9461	1.40283	3.272667	1.1963851	1.109518919
8	13.6359	1.57941	4.471	1.2203253	1.186828785
9	3.7278	0.74556	6.282333	1.1867957	1.196385052
10	1.2753	0.93195	7.266333	1.1282016	1.061241587
11	7.7499	0.96138	8.732333	1.2403968	1.198309532
12	7.4556	0.86328	5.244333	1.251904	1.220927131
13	16.9713	0.42183	10.56633	1.2748655	1.216959131
14	10.4967	0.48069	8.170667	1.1973572	1.159052785
15	3.8259	0.87309	4.725	1.1868288	1.220325318
16	12.8511	1.03986	6.964667	1.2059744	1.206933318

Table 4: Overall Performance Index (OPI), Corresponding S/N Ratios (of OPIs) and Predicted S/N Ratios

OPI by TOPSIS	OPI by Deng's Similarity Method	Corresponding S/N ratio TOPSIS	Corresponding S/N Deng's Similarity Method	Predicted S/N Ratio (TOPSIS)	Predicted S/N Ratio (Deng's Similarity Method)
0.735714028	0.705737476	-2.665819266	-3.027136405		
0.609318215	0.682315862	-4.303116778	-3.320290647		

0.388134092	0.658213474	-8.220364172	-3.632664631		
0.059093032	0.625483138	-24.56927458	-4.075687874		
0.567107	0.671103732	-4.926699846	-3.464206925		
0.487739182	0.663120971	-6.23624708	-3.568144746		
0.567172173	0.675022134	-4.925701694	-3.413639726	2.57546	-2.76218
0.391085254	0.648413601	-8.154571168	-3.762957687		
0.744386219	0.704364506	-2.564033512	-3.044050735		
0.706415709	0.704365556	-3.018793036	-3.044037795		
0.512669447	0.67461764	-5.803251274	-3.418846144		
0.649762985	0.688031776	-3.744900657	-3.247830082		
0.380252326	0.643475641	-8.398562404	-3.829357779		
0.544262978	0.6695644	-5.283824123	-3.484152901		
0.760079881	0.706816501	-2.382815263	-3.013866409		
0.406552098	0.654691051	-7.817675863	-3.679271905		

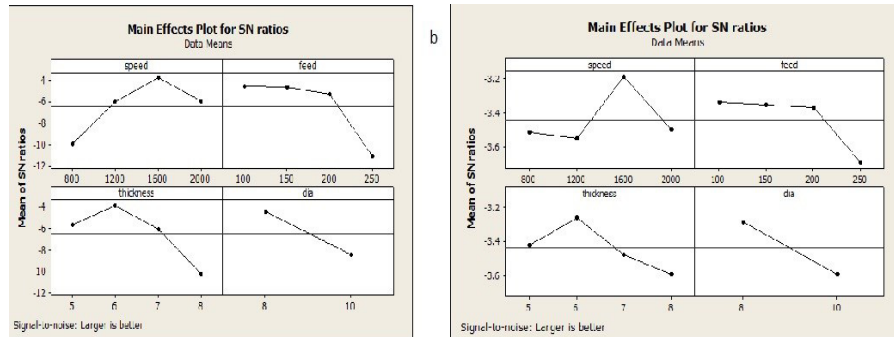


Fig. 2: Evaluation of optimal parametric combination by using (a) TOPSIS (b) Deng's Similarity Based Method in conjugation with Taguchi approach

## 6. Conclusion

The present study aimed investigate the optimal drilling parameters setting based on minimum of the thrust forces, torque, surface roughness, damage factor and thereby attaining defect free drilling of GFRP composites using TiAlN coated solid Carbide drill bits, according to the  $L_{16}$  orthogonal array experiments. Optimal parametric combination obtained from TOPSIS and Deng's similarity methods have been found similar to each other. Experimental approach illustrates the feasibility and effectiveness of these proposed methodologies for optimizing the drilling parameters to achieve better quality holes in GFRP composites.

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